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Product-Service Systems across Life Cycle

Development of a Whole Life Cycle cost model for electrification options on the UK rail system

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Abstract

Projects to deliver Overhead Line Equipment (OLE) electrification on the UK rail infrastructure system presents technical challenges which the rail industry in Britain have not traditionally had to consider. Whole Life Cycle assessment provides decision makers with cost estimates for the installation phase and over the entire service life of the system, including disposal. The OLE projects face a particular problem when analysing the best option for overbridges. Much of the rail infrastructure has not traditionally had to consider overhead clearances and therefore many of the bridges are only a little taller than the rolling stock. In addition to the difficulties in assessing the Life-Cycle costs of assets that have historically been used in very limited scales, the Whole Life Cycle assessment must consider the various engineering options that are available for projects. The three competing options (bridge rebuild, track lowering, reduced clearance) are all going to have very different capital expenditure (CAPEX) and operating expenditure (OPEX) costs. This work presents a model created to predict these costs over the anticipated assessment period. The developed model predicts capital expenditures, maintenance and service disruption costs and links them to the three major assets options involved in OLE underbridges.

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Keywords: whole life cycle; rail maintenance; OLE; cost

1. Introduction

Network Rail are facing challenges with the extension of the electrification system to the network, because electrified routes provide not only 'faster, quieter and more reliable journeys' for passengers and freight transportation, but also a reduction of up to 35% in carbon emissions [1]. The Overhead Line Equipment (OLE), supplies electrical power to trains by means of contact wires suspended over the track. The electrification project includes considerable civil engineering modifications to railway assets. These are expected to be particularly challenging at particular features on the network, particularly in proximity of overbridges. Network Rail define Overbridges as "to carry another service (such as roadways, footways and public utilities) over the railway".

A product breakdown structure of an OLE would include the following [2]; Contact wires, Messenger wires, Droppers (which link messenger wires to contact wires) and Steady arms (maintaining a zigzag shape of contact wires to prevent uneven wear).

For many railway overbridges, the expected gap between power cables and the ceiling are inadequate to comply with the European standards for electrical clearances. Major alterations are required on the railway infrastructure. Three options are relevant: Bridge reconstruction, Track lowering and Reduced clearances.

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Bridge reconstruction: Where the bridge is demolished and replaced with a newer bridge capable of accommodating the required clearance of electrical equipment. Capital expenditures are expected to be mostly related to demolition, reconstruction of the overbridge and OLE installation costs [3]. This option is expected to be favourable for maintenance expenditure, due to the OLE clearance minimising problems and the condition of the reconstructed bridge being excellent.

Track lowering: Existing rails and ballast are first removed to allow for digging the soil on the approaches to the overbridge. A new drainage system installed, together with new ballast and new rails. This solution involves considerable denial of service costs during initial engineering works and can lead to greater maintenance expenditure for tracks, because rails, ballast and drainage are affected by stagnating water during rainy periods [3]. Lowering the track to increase the clearance between the OLE and rolling stock is an option likely to alleviate the OLE problems but could introduce significant issues with water ingress onto the track and subsequent damage to the track, ballast and sleepers.

Reduced clearances: It is possible to install OLE that gives much less room between the live wire and the rest of the support structure. This reduced clearance results in slower speed limits through that section of the track, making it unsuitable on very busy lines. However, required alterations are less substantial and solution presents the lowest capital investment of the three options. Reduced clearance OLE is suspected to be particularly prone to electrical trips.

In addition, the height of the cables under the overbridge is lower than on open routes so that a gradient is present while approaching the bridge which generates increased amounts of wear on contact wires as a consequence of the greater forces acting between cables and pantographs. Reduced clearances raise specific concerns regarding increased fault occurrences, possession times and negative impacts on the organisations reputation. The difficulty with accepting a lower clearance is that the maintenance costs are anticipated to be much higher; over the 60 year assessment period this may well prove to be disastrous to cost. Maintenance problems can also cause issues with asset availability, and the decision making process is very sensitive to denial of service of the infrastructure system.

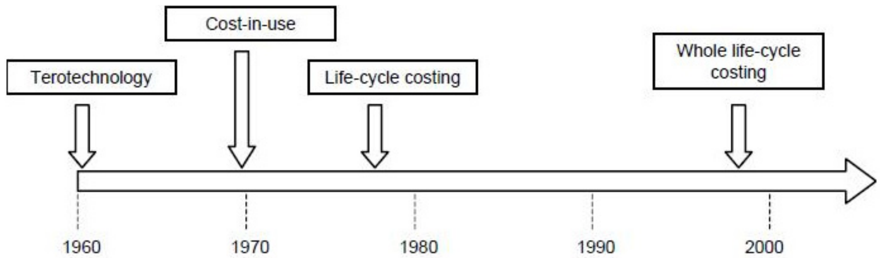

Figure 1: The evolution timeline of WLC costing model [4]

The installation of the electrical system to overbridges is a requisite for the complete electrification of rail routes. However, the decision-making process will be looking for the best compromise between capital investments and maintenance costs occurring over a defined period of time. A final complication with adjusting overbridges is that many of them are considered part of the UK's historical and architectural heritage (particularly those that are from the Victorian era) and are protected by Government legislation. The industry is therefore interested in assessing other options beyond bridge demolition and reconstruction.

1.1 The AUTONOM project

The AUTONOM project at Cranfield is seeking to develop cross-industry approaches to the difficulty with integrating condition monitoring to automated planning/scheduling and cost estimation. Cost of a maintenance activity prompted from an alerted change in condition, will be optimised as much as possible (through scheduling at cost effective times). The project is also seeking to model the whole-life costs arising from maintenance interventions, so that cost savings can be realised by the integrated approach.

1.2 Whole Life Cycle cost modelling

Whole Life Cycle costing is a structured methodology that helps decision-makers in selecting the option that minimises the sum of all relevant costs occurring over the whole service life of a product, system or service [4].

The concept was gradually developed during the last sixty years, as figure 1 shows. Before the 1960s, capital investment decisions were drawn basically on the basis of capital costs, because the general belief was that, along with increasing initial investments, decreasing long-term expenditures would be consequently experienced (Terotechnology). The concept then evolved to 'cost-in-use' with a consideration of the costs associated with also the operations of an asset, [4].In the late 1970s, analysts and accounting managers began introducing forecasting techniques for the evaluation of future costs (Life Cycle Costing) but the method was adopted only for projects with large capital investments.

Towards the end of the last century, the technique evolved to 'Whole Life-cycle Costing', which differs from LCC by considering costs occurred over not only the economic life (the period of commercial interest) but rather over the entire life of a product or service (i.e. disposal costs are considered).

1.3 Application of WLC to the railway industry

The railway industry has challenges when applying WLC methods. In particular, assets have extended life spans and capital investments are considerable. Decisions about maintenance strategies need to be considered from a whole life cost perspective. Andrade [5] outlined specific challenges for the application of a long-term approach to the rail industry:

- Lack of data on maintenance costs
- Lack of data on degradation of different components of the infrastructure
- The acquisition of data is not always timely for swift decision-making processes
- Asset degradation rates are slower, therefore needing more time for data collection
- In case of asset breakdown, consequential costs can be difficult to assess

It is worth mentioning railway assets and people are distributed over a large area, diversity, in terms of component behaviour and asset lives, and interactions between system components adds complexity [6].

2. Asset degradation models

The main factor that drives failures and maintenance is the degradation of the asset [7]. An asset degradation model describes how components or systems deteriorate their ability to perform required functions and can be assumed to correlate with maintenance effort and therefore costs.

Asset	Expected Asset Life (years)
Overbridge	150
OLE	40+
Track	10-40 (MGT dependent)

Table 1: Expected Asset life

The collected expected asset-life values are gathered in table 1. While OLE and track are systems with subsystems that degrade at different rates, for this work these assets are modelled at the system level.

Track: There is a general expectation that track degrades according to a negative exponential-like equation [8-10]. Track degradation is expressed as a function of time even if the main factor responsible for degradation is the weight of traffic on the route (measured in MGT/year), [9] in equation 1.

$$Q(t) = Q_0 * exp[-b.t] \qquad (1)$$

The quality of the track Q (t) over each year of the planning horizon t depends upon the quality at renewal time Q_0, set conventionally at 100% and the degradation rate *b*.

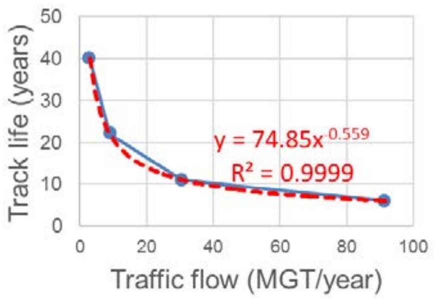

Figure 2: Expected track degradation

Expected life of tracks can be derived from data adapted from Baumgartner, [11].

Overbridge: Models of railway overbridges tend to be complicated. An approachable model that relates the condition of the asset to its age can be found in Le and Andrews [12]. The mathematical expression is a third-degree polynomial that returns for each year (t) a value on a 0-to-7 scale, where the 0-7 scale indicates condition of the asset. This degrading condition is considered to be only a factor of age and not of usage. As the expected asset lifecycle is approximately 150 years the change in maintenance costs over the 60 year assessment change relatively little.

Overhead Line Equipment: The degradation process of the OLE system is complicated as different components are designed for different technical life expectancies. Duque et al. [13] uses records of system failures from the previous 17 years and finds that annual failure rates for different components are of very low orders of magnitude. Researchers have calculated the average life span of contact wires as 15 years, while the remaining components maintain their operations for 40 years or more [14-16]. For this work is assumed that the OLE system will degrade using the same exponential form as the track, but obviously using different constants. This is a bit of an abstraction as in reality OLE is a system made of sub-systems that degrade at different rates (for example the structures are likely to maintain their condition for much longer than the contact wires). This approach does have advantages though as we see the OLE condition responds to higher track usage and maintenance proportionately rises.

3. Developed Cost model

In the new WLC cost model data related to assets conditions, route features, times and costs from past projects are used as inputs. The outputs are the WLC costs over the next sixty years for each considered option, broken down into CAPEX and OPEX costs. Four steps proposed by Zoeteman [7] were included and are important because they link expected traffic flow, (MGT) to the condition of the asset:

1. Estimate the loads of the track section
2. Estimate asset condition for each year of the planning horizon
3. Estimate total maintenance costs, based on assets condition
4. Estimating life cycle costs, by summing up all the costs incurred over the assessment period

The previously defined asset degradation models for the three assets involved in infrastructure alterations: tracks, overbridges and OLE are used. For each asset the WLC costs are structured in terms of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

Capital expenditures: Capital expenditures occur during the initial year of the project and are assumed not to incur costs in subsequent years (through financing issues). All three scenarios include standard OLE installation costs, except in the reduced clearance case where an adjustment has been made to account for the additional flash-over protections and more specialised equipment.

Operational Expenditure: Tracks and overbridge maintenance costs are modelled using linear relation with condition of the assets. In addition to maintenance costs renewal costs are triggered when the condition of the asset falls below the renewal threshold. Renewals represent significant efforts to return an asset to "good as new". Renewal thresholds can be set individually for OLE, Overbridges and Track by the user. Maintenance cost inputs include average pay rate for relevant asset maintenance team and average time for repairs (with each asset accepting different values). Track requires more inputs; such as delay costs (pounds/minute/track), number of tracks and approximate frequency of trains.

4. WLC Model Output

For the sixty year assessment period, the behaviour of the assets are modelled for each year. Modelling takes predictions of asset condition based on age and/or usage and predicts maintenance costs of that asset for each of the scenarios. Maintenance costs are calculated in this way for each year in the assessment period before results are presented in graphical form, showing the breakdown of CAPEX and OPEX expenditure for the three scenarios.

The following figure shows the costs for each of the explored scenarios and the split between CAPEX and maintenance costs. Some details had to be assumed for the analysis. In the example results shown track lowering is the most expensive option in a major part due to high estimated CAPEX costs.

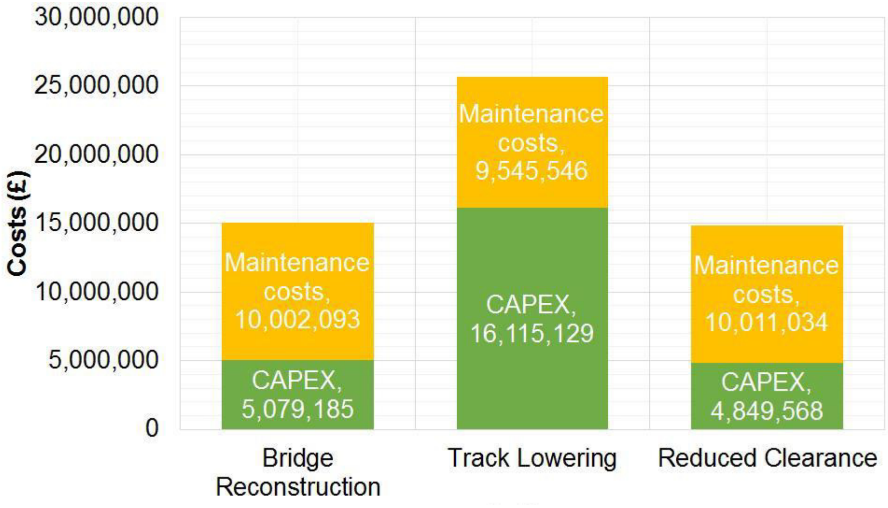

Figure 3: graphs of estimates generated by the tool

Some values used during the model have had to be estimated or taken from various open source information. Therefore this prediction should not be used as the exclusive analysis for policy decision making.

The purpose of this work was to provide a tool for structuring the analysis and guiding further work- in particular identifying the factors most likely to influence the WLC costs associated with the three OLE options will be valuable in future analysis.

The cost model development methodology has a strong focus on asset degradation and condition as the main cost drivers of maintenance costs. This decision would make the model usable and further developable by the AUTONOM Project.

The structure of the tool enables future users to consider additional groups of costs, such as safety risk costs. Accurate denial of service estimates are also clearly of interest for the accuracy of the estimates. A sensible future objective for the project is expansion of the model to consider additional options such as 'neutral sections'.

With additional findings the 'reduced clearance' analysis could be modified to examine the 'neutral section' technical option. The 'neutral section' option would need to include the low-probability/high-impact risk event of an electrical train losing power under a bridge.

5. Conclusions and further work

This work has provided a Whole Life Cycle cost model that accounts for the infrastructure modifications (tracks, overbridges and OLE) over a 60-years planning horizon. It includes capital expenditures and maintenance costs, with related possession and delay costs when the activities are performed.

Visualisation of the competing options allows the user to easily and quickly compare both the total cost estimated and the components of that cost attributable to CAPEX and OPEX expenditures.

The tool has been developed to consolidate information within the available literature and provide an estimate of likely WLC costs of the OLE underbridge projects. Future work will seek to validate the model presented here through comparison with Network Rail models and their techniques for WLC estimation.

It is understood that Network Rail operates a bottom-up WLC cost model called CoBALT. The comparison with our top-down type of WLC cost model will be of interest as the method presented in this paper requires less detailed information and generates estimates more quickly.

Future work will also seek to generate OLE specific Asset Lifecycle Profiles (ALP). These ALP's form an essential part of the CoBALT WLC model at Network Rail. The detailed bottom-up whole-lifecycle assessments they generate are clearly of interest to other organisations that are responsible for cost-effective asset management. Most obvious are the other rail industry bodies within the UK, such as London Underground, or HS1. When the interest is expanded further to the maintainers of linear infrastructure, roads, water, electrical power and oil/gas industries are all likely to face similar cost estimation challenges.

Using multiple estimates generated from different methods is a very strong process for having useful business decision making information. Building estimates from a top-down and bottom-up method can help add validity to each other. In the situations where estimates disagree, much more can be learned and the process refined as root causes for the disagreement are found.

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